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Abstract: Neglected or incorrect treatment of pediatric radial neck fractures may lead to symptomatic malunions. Computer-assisted corrective osteotomies with patient-specific guides have been proposed as a promising technique for the reconstruction of malunited long bone deformities. The aim of this study was to evaluate the accuracy and clinical outcome of this technique in children with malunited fractures of the radial neck. Four children (two male, two female; mean age 12 (10-16) years) underwent computer-assisted closing wedge osteotomy of the radial neck. The contralateral uninjured side was used as a reconstruction template. CT scans were performed eight weeks postoperatively to confirm bony consolidation and to quantify residual 3D rotational and translational displacement error. Clinical outcome (pain, range of motion) and overall satisfaction were documented. Preoperative subluxation of the radial head could be corrected in two of three patients. One patient had to be revised due to secondary traumatic loss of reduction. At the last follow-up (mean 16 (range, 12-24) months), all patients were pain free for activities of daily living (preoperative pain: visual analogue scale 6). Pain during sport activities could be substantially reduced (visual analogue scale 8→2). Although the procedure failed to improve range of motion, none of the patients had limitations regarding work, daily or sports activities. Yet, restricted range of motion was considered as a cosmetic problem in one patient. Full consolidation of the osteotomy site, with no signs of avascular necrosis of the radial head, was achieved in all patients. The deformity could be substantially reduced, from a 3D angle of 13-40° to 3-7° (58-89% deformity correction). Computer-assisted corrective osteotomy is a novel technique for the treatment of radial neck malunions that led to adequate pain reduction and 3D accuracy of deformity correction in our small case series. Despite the lack of improved range of motion, all patients were satisfied and would undergo the same procedure again. LEVEL OF EVIDENCE Level IV, Case Series, Treatment Study.

DOI: https://doi.org/10.1097/BOT.0000000000000970

Originally published at:
Weigelt, Lizzy; Fürnstahl, Philipp; Schweizer, Andreas (2017). Computer-assisted corrective osteotomy of malunited pediatric radial neck fractures - Three-dimensional postoperative accuracy and clinical outcome. Journal of Orthopaedic Trauma, 31(12):e436-e441.
DOI: https://doi.org/10.1097/BOT.0000000000000970

Journal of Orthopaedic Trauma Publish Ahead of Print
DOI: 10.1097/BOT.0000000000000970

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None of the authors have received at any time payment or services from a third party (government, commercial, private foundation, etc.) for any aspect of the submitted work.

Conflict of interest statement:
The authors, their immediate families, and any research foundation with which they are affiliated did not receive any financial payments or other benefits from any commercial entity related to the subject of this article.

This work was presented as a poster presentation at the 17th EFORT Congress 2016 in Geneva.

Summary: Neglected or incorrect treatment of pediatric radial neck fractures may lead to symptomatic malunions. Computer-assisted corrective osteotomies with patient-specific guides have been proposed as a promising technique for the reconstruction of malunited long bone deformities. The aim of this study was to evaluate the accuracy and clinical outcome of this technique in children with malunited fractures of the radial neck. Four children (two male, two female; mean age 12 (10-16) years) underwent computer-assisted closing wedge osteotomy of the radial neck. The contralateral uninjured side was used as a reconstruction template. CT scans were performed eight weeks postoperatively to confirm bony consolidation and to quantify residual 3D rotational and translational displacement error. Clinical outcome (pain, range of motion) and overall satisfaction were documented. Preoperative subluxation of the radial head could be corrected in two of three patients. One patient had to be revised due to secondary traumatic loss of reduction. At the last follow-up (mean 16 (range, 12-24) months), all patients were pain free for activities of daily living (preoperative pain: visual analogue scale 6). Pain during sport activities could be substantially reduced (visual analogue scale 8→2). Although the procedure failed to improve range of motion, none of the patients had limitations regarding work, daily or sports activities. Yet, restricted range of motion was considered as a cosmetic problem in one patient. Full consolidation of the osteotomy site, with no signs of avascular necrosis of the radial head, was achieved in all patients. The deformity could be substantially reduced, from a 3D angle of 13-40° to 3-7° (58−89% deformity correction). Computer-assisted corrective osteotomy is a novel technique for the treatment of radial neck malunions that led to adequate pain reduction and 3D accuracy of deformity correction in our small case series. Despite the lack of improved range of motion, all patients were satisfied and would undergo the same procedure again.

Level of Evidence: Level IV, Case Series, Treatment Study

Keywords: Corrective osteotomy; radial neck; malunion; patient-specific guides; computer-assisted; computed tomography; pediatric

INTRODUCTION

Radial neck fractures represent 5-10% of all pediatric elbow injuries[1–3]. There is common agreement that the treatment algorithm should be based on the initial displacement and angulation deformity of the fracture[4–8]. Most of these fractures may be treated non-operatively. In radial neck fractures with severe angulation and displacement closed reduction may be necessary, whereas open reduction should be reserved for all cases that remain irreducible[7]. Nevertheless, there is no clear consensus what amount of residual deformity is deemed acceptable, with thresholds ranging from 15° to 45°[5,7,9,10]. Regardless the initial fracture treatment, fair to poor outcomes have been documented after 9-32% of all radial neck fractures[3–7]. Possible complications are avascular necrosis and overgrowth of the radial head, radioulnar synostosis and symptomatic malunions[7]. In earlier studies, malunions after radial neck fractures have been reported in 0-33% of the cases[4,7,11]. However, all of these studies evaluated the deformity only two-dimensionally based on conventional radiographs[5,12]. Therefore, a substantial amount of malunited fractures, especially those with rotational errors, may have been missed. Some patients with apparently little residual deformity showed poor results[3,5,8], which might support this assumption.

Computer-assisted corrective osteotomies, based on computer simulation and patient-specific guides, have been described as a promising technique for reconstruction of malunions in the upper and lower extremities[13–16]. Three-dimensional (3D) computer-assisted planning may help to understand the deformity and plan the correction more thoroughly. The guides that are manufactured for intraoperative use may facilitate surgery and improve precision of the osteotomy[16].

To date, this method has not been reported for the reduction of malunited fractures of the radial neck. The aim of this study was therefore to assess the accuracy and the clinical outcome of this technique in a small case series of four children with radial neck malunions.

METHODS

Demographics and initial presentation

Between May 2013 and November 2014, four consecutive cases of children at the age of 10 to 16 years with malunited radial neck fractures were treated with computer-assisted corrective osteotomy. None of the children presented immediately at our clinic after the trauma. The mean period between the trauma and the corrective osteotomy was 18 months (Table 1). Case 1 initially showed a complete dislocation of the radial head, which was promptly treated with open reduction and K-wire fixation (see Figure, Supplemental Digital Content 1 http://links.lww.com/JOT/A92, which demonstrates the radiological evaluation of case 1). The K-wires were removed four months later. Case 2 and 3 were first treated non-operatively with temporary splint immobilization of the elbow. In case 4, there was no memorable trauma and therefore no treatment before presentation in our clinic. All patients complained about stress-related pain (Table 1), crepitation and limited range of motion (ROM) in daily and sport activities prior to surgery (Table 2). All patients favored a proactive treatment approach because of their substantial impairment in quality of life, mainly due to pain rather than limited ROM. Computed tomographic (CT) scans of both forearms were performed for preoperative planning. Informed consent was obtained both from the patients and their parents. The local responsible Ethics Committee approved the study.

Preoperative planning and surgical technique

Based on bilateral CT scans (Philips Brilliance 40 CT; 120kV; Philips Healthcare, Best, The Netherlands; slice thickness 1 mm), 3D bone models of the patients' pathologic and contralateral healthy forearms were extracted by using the segmentation function of Mimics software (Materialise, Leuven, Belgium). The bone models were imported into the in-house developed planning software CASPA (Balgrist CARD AG, Zurich, Switzerland). The mirror-model of the contralateral healthy radius was used as a reconstruction template. The part of the pathological radius located distal to the malunion was superimposed on the corresponding region of the template by applying the Iterative Closest Point (ICP) surface registration algorithm[13] (Figure 1A). The osteotomy site was defined at the level of the radial neck by a virtual cutting plane that could be modified in 3D space (Figure 1B). Next, the malunited radial head was virtually separated and aligned to the contralateral radial head template with ICP (Figure 1C). The required reduction was assessed in six degrees of freedom based on a standardized coordinate system. The origin of the coordinate system was defined in the center of the malunited radial head. The x-, y- and z-axis were defined as parallel to the longitudinal axis of the radial shaft, the flexion/extension and valgus/varus angulation of forearm, respectively. Based on these axes, three rotational (pronation/supination, flexion/extension and valgus/varus angulation) and three translational (proximal/distal, volar/dorsal and radial/ulnar displacement) values were measured. Furthermore, the 3D angle was calculated as a summary of the rotational deformity in the 3D space (see Table, Supplemental Digital Content 2 http://links.lww.com/JOT/A93, which demonstrates the accuracy of 3D corrective osteotomy). Preoperative planning also included the design of patient-specific guides, using the same software (Figure 1D). The guide bodies were molded on the irregular shaped bone surface and thus uniquely fitted to the planned osteotomy site on the pathologic radius, which facilitated the intraoperative positioning of the guides and the subsequent reduction. The guides were manufactured, using a selective laser-sintering device (Medacta, Castel San Pietro, Switzerland). Sterilization was performed with conventional steam pressure.

Except for the first surgery of case 1, all corrective osteotomies were planned and performed by one senior surgeon (last author) through a classical Kocher approach with subsequent detachment of the supinator muscle to expose the proximal part of the radius. After meticulous dissection of the soft tissue, the drill guides were applied to the bone. The osteotomy was guided by setting consecutive drill holes (3-4 mm spacing) along the osteotomy plane. Drill sleeves were integrated into the corresponding osteotomy guide (Figure 2A). After removal of the guide, the osteotomy was completed with a cannulated chisel (Figure 2B). In all cases, the reduction could be performed through a biomechanically favorable closing wedge osteotomy (Figure 2C). Furthermore, the osteotomy guide contained additional drill sleeves that secured proper fixation of the guide to the proximal and distal fragment with K-wires. After completion of the osteotomy, a reduction guide was put over the proximal and distal K-wires and the proximal fragment was brought into its reduced position (Figure 2D). In the first two cases, fixation was performed with intramedullary nails (Elastic Stable Intramedullary Nailing, Synthes, Oberdorf, Switzerland), which were inserted in retrograde direction and driven forward over the osteotomy site. Due to the questionable stability of these implants, the fixation technique was changed to plates (Locking Compression Plate, Synthes, Oberdorf, Switzerland) in the last two cases (Table 1).

Postoperative treatment protocol and patient evaluation

After surgery, a dorsal splint was applied for eight weeks. Physiotherapy assisted passive mobilization to regain flexion and extension ROM was started two weeks after surgery. Pro- and supination was prohibited for the first four to eight postoperative weeks, according to the intraoperatively judged stability of the osteosynthesis.

All patients revisited for clinical and radiological evaluation at our outpatient clinic eight weeks postoperatively. CT scans were obtained to determine the consolidation of the osteotomy, which was defined as the presence of continuous bone trabeculae of at least half of the diameter of the osteotomy plane[16]. The CT scans were also used for the evaluation of the accuracy of the reduction. As introduced in previous studies, the severity of the deformity before and after surgery was assessed[14,16]: After re-performing the segmentation of the postoperative CT data, the 3D difference between the radial head in postoperative and planned reduced position was measured, resembling the residual error. The deviation to the preoperative plan was expressed in all six degrees of freedom using the same standardized coordinate system as described above (see Table, Supplemental Digital Content 2).

RESULTS

All patients were pain free for activities of daily living at the last follow-up (mean 16 (range, 12-24) months). Furthermore, pain during sport activities could be substantially reduced (Table 1). The preoperative ROM restrictions, affecting mainly pro- and supination, could not be improved (Table 2). All patients underwent implant removal and intraoperative elbow joint mobilization after osseous consolidation of the osteotomy and adequate physiotherapeutic rehabilitation. Still, they showed persistent or even deteriorated pro- and supination ROM restriction at the last follow-up. Nevertheless, all patients stated that these restrictions did not affect their work, regular daily life or sports activities. One patient considered the limited ROM as a cosmetic problem. All of them were very satisfied with the postoperative course and the clinical outcome and affirmed that they would undergo the procedure again. In three of four patients bony consolidation was completed eight weeks postoperatively. Case 3 showed delayed union of the osteotomy site (see Figure, Supplemental Digital Content 3 http://links.lww.com/JOT/A94, which demonstrates the radiological evaluation of case 3); however, full consolidation was reached four months postoperatively. No avascular necrosis of the radial head was detected. Angulation deformity could be reduced from 13-40° to 3-7°, which resembled a deformity reduction of 58−89% (see Table, Supplemental Digital Content 2)

Case 1 initially showed a partial closure of the proximal radial physis. Since computer-assisted corrective osteotomy was not available at our clinic at that time, an epiphysiodesis was performed two years after the initial trauma to prevent further progression of the deformity. Two years later, the patient reported progressive pain and limited ROM. CT scans displayed a flexion deformity at the level of the radial tuberosity and a subcapital varus deformity with subluxation of the radial head. The preoperative planning showed the need for a double plane corrective osteotomy with removal of two wedges at the level of the described deformities. Fixation was reached with an intramedullary nail. After consolidation of the osteotomy sites, implant removal was performed three months after surgery to improve ROM. The patient was pain free for eight months until she sustained a skiing accident with fall on the affected left elbow. CT scans showed correct subcapital alignment, but recurrence of the deformity at the level of the radial tuberosity. Furthermore, degenerative changes of the capitellum and the radial head, with enlargement of the latter, could be detected. Another revision with re-correction of the deformity and slight shortening of the radius, for pressure reduction in the radiocapitellar joint, was planned through a closing wedge osteotomy. This time, fixation was performed with a radial head plate, which was removed six months later (see Figure, Supplemental Digital Content 1).

Preoperative 3D analysis revealed subluxation of the radial head in two other cases (see Figure, Supplemental Digital Content 4 http://links.lww.com/JOT/A95, which demonstrates the radiological evaluation of case 2; Figure 3A). In case 2, the subluxation was persistent in the first postoperative control, but spontaneously resolved until the last follow-up of 12 months. In case 4, the subluxation could not be resolved (Figure 3C, D). The radial head itself was deformed depicting an angulated biconcave joint surface instead of a symmetric fovea (Figure 3B), which may explain the failure of reduction. Both the radial head and the corresponding humeral capitellum showed central cartilage lesions. The cartilage was adjusted to the corresponding joint surface of the capitellum by careful chondroplasty.

DISCUSSION

Computer-assisted corrective osteotomy for the treatment of radial neck malunions in children is a novel technique that led to adequate pain reduction and 3D accuracy of deformity correction in our small case series. The 3D angle of deformity could be reduced from 13-40° to 3-7°, which is a slight inferior result in terms auf accuracy compared to other studies reporting on corrective osteotomies in longbone deformities[16,17]. However, the radial head fragment is substantially smaller compared to the fragments in diaphyseal or distal radial osteotomies. Even after a correctly performed osteotomy, stable fixation of this fragment in the planned position is challenging and may explain the somewhat poorer reduction. This also persuaded us to change the fixation technique after the first two cases in favor of locking compression plates that showed higher primary stability. Contradicting the accurate radiological reduction, all patients in our study had substantially restricted ROM at the latest follow-up that was even worse than it was before the corrective osteotomy in almost all directions of motion. It may be assumed, that not only the bony deformity, but also the surrounding soft tissues may play an important role in the development of restrained ROM in forearm deformities. These structures include a contracted interosseous membrane, restricted proximal and distal radioulnar joint capsules and other surrounding soft tissues that may prevent improvement of ROM after adequate osseous reduction[18]. On the other hand, the postoperative loss of ROM may have also been related to the relatively long postoperative immobilization period of four to eight weeks for pro- and supination. The primary goal was however to achieve osseous consolidation of the radial head fragment in the correct position, which was very small and thus prone to secondary dislocation. Despite the ROM restrictions, the four patients were pain free regarding daily activities, only showed mild symptoms during sports activities and were satisfied with the postoperative clinical outcome. With the exception of the recurrent deformity in case 1, which was caused by another adequate trauma to the affected elbow, we did not detect any other complications, previously described for open procedures on the proximal radius[5,7,19,20].

Whereas several rescue procedures, including radial head resection or arthroplasty[21–23], have been described for malunited fractures of the radial head, there is a lack of evidence for the correct treatment indications and procedures for isolated malunions of the radial neck. Complications of radial head excision are potential posterolateral instability as well as ulnohumeral arthritis and impingement, caused by proximal migration of the radius[1]. It seems reasonable that the radial head should be preserved in children, whenever possible, because long-term effects of radial head excision may not be predicted at this stage[24,25].

Corrective osteotomies are established procedures for treating long bone deformities[16,17]. For symptomatic radial neck malunions, they have only recently been proposed in small case series[26,27]. Vandergugten et al.[27] treated a 33-year old woman with a closing wedge osteotomy of a malunited radial neck fracture that the patient sustained at the age of eleven. A dorsal angulation deformity could be reduced from of 60° to 0°. Fixation was reached with three intraosseous headless screws. Ceroni et al.[26] performed a closing wedge osteotomy and intramedullary nail fixation in two children with severe malunion of the radial neck. In both cases, adequate congruency of the radioulnar and radicapitellar joint could be achieved on plain radiographs. Besides premature closure of the proximal radial physis, no other complications occurred. In both studies, good results regarding pain relief, ROM improval and deformity correction could be achieved. However, the deformity was only analyzed two-dimensionally on conventional radiographs, which makes the quantification of the deformity in axial direction difficult, if not impossible at all. Furthermore, the exact technique of the closing wedge osteotomy to achieve adequate correction was not described.

This study has several limitations. First, documentation of ROM at the final follow-up was performed by several investigators, which might have had an effect on the consistency of the results. However, reviewing the other postoperative controls, the ROM in each patient remained more or less the same during the course of time. In no case, ROM could be substantially improved after implant removal. Second, the mean follow-up period of 16 months is short. ROM may still improve in the children during growth, since remodeling of the surrounding soft tissues may occur. Third, we only present a case series of four patients. On the other hand, the treatment of radial neck malunions is scarcely discussed in literature and only case reports have been published[26–28]. Despite the lack of improved pro- and supination ROM, all patients were satisfied at the last follow-up and would undergo the same procedure again. Finally, we found beginning degenerative changes in the elbow joint in three of the four cases (see Figure, Supplemental Digital Content 1 and 4; Figure 6D) at the last follow-up. It cannot be predicted to what extent these changes might cause problems in the long term. Therefore, the indication of such a deformity correction must be carefully considered. It should be mainly conditional upon the children's suffering. Larger cohort studies and longer follow-ups are therefore needed to confirm the advantages of this procedure for these kinds of malunions.

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FIGURE LEGENDS

FIGURE 1. Computer-assisted planning of case 3. **A** Superimposition of the contralateral healthy radius (green). **B** Determination of the osteotomy plane and separation of the malunited radial head (pink). **C** Alignment of the malunited radial head (pink) to the template (with slight shortening). **D** Applying the patient-specific guide.

FIGURE 2. Corrective osteotomy of case 3 with patient-specific guides. **A** Osteotomy guide with incorporated drill sleeves. **B** Completion of the osteotomy with cannulated chisel. **C** Wedge removal. **D** Closing of the osteotomy site with reduction guide.

FIGURE 3. Radiological evaluation of case 4 **A** Preoperative dorsal subluxation. **B** Intraoperative biconcave facet of the radial head. **C** CT scans 8 weeks postoperatively and **D** plain radiographs at last follow-up with persistent subluxation of the radial head.

TABLE 1. Demographics and pain documentation

		Demographics						Pain preop/postop		
Case	**Osteotomy**	**Age at surgery, y**	**Injury to operation, mo**	**Implant type**	**Implant removal, mo**	**Last clinical FU, mo**	**FU at call, mo**	**Rest**	**ADL**	**Sports**
1	(05/2013)	(10)	(5)	(nail)	(3)	(29)	(35)			
	07/2014	11	15	plate	12	15	21	0/0	3/0	7/3
2	04/2014	10	7	nail	2	12	24	0/0	8/0	9/0
3	04/2014	16	42	plate	9	24	24	0/0	4/0	8/0
4	11/2014	11	*	plate	4	12	17	0/0	2/0	7/0

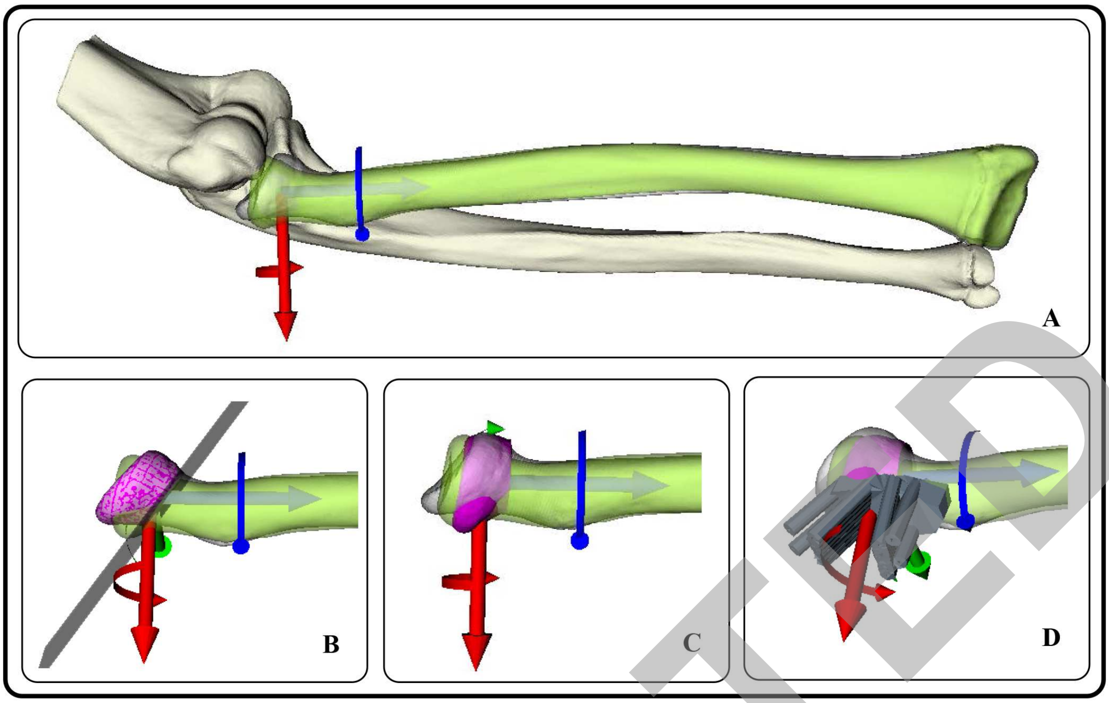
y, years; mo, months; °, degrees; *, no memorable trauma

Demographical data as well as pre- and postoperative pain scores (noted as visual analogue scale (0-10 points)) are displayed. Corrective osteotomy was performed twice in case 1 (data of the first osteotomy in parentheses).

TABLE 2. Pre- and postoperative range of motion compared to the contralateral healthy elbow.

Case	ROM (°)	Preoperative	Postoperative	Contralateral
1	Flex/Ex	150-0-0°	130-0-0°	150-0-5°
	Pro/Sup	70-0-40°	70-0-30°	80-0-80°
2	Flex/Ex	130-30-0°	120-20-0°	150-0-5°
	Pro/Sup	50-0-70°	40-0-50°	80-0-85°
3	Flex/Ex	150-20-0°	140-30-0°	150-0-0°
	Pro/Sup	70-0-50°	45-0-40°	75-0-75°
4	Flex/Ex	150-10-0°	140-5-0°	150-0-0°
	Pro/Sup	10-0-10°	20-0-20°	80-0-70°

Flex, Flexion; Ex, Extension; ROM, range of motion; °, degrees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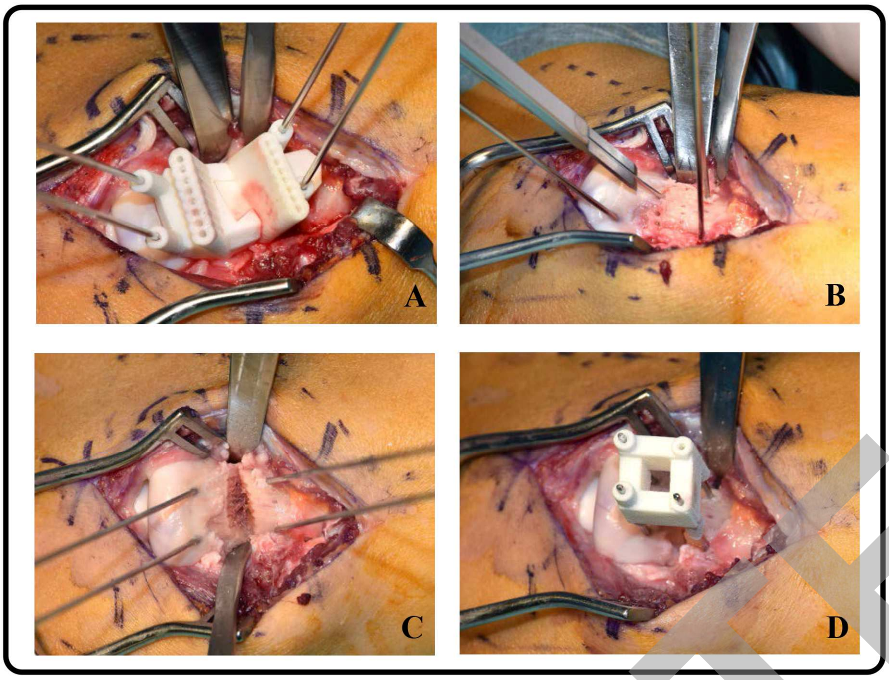
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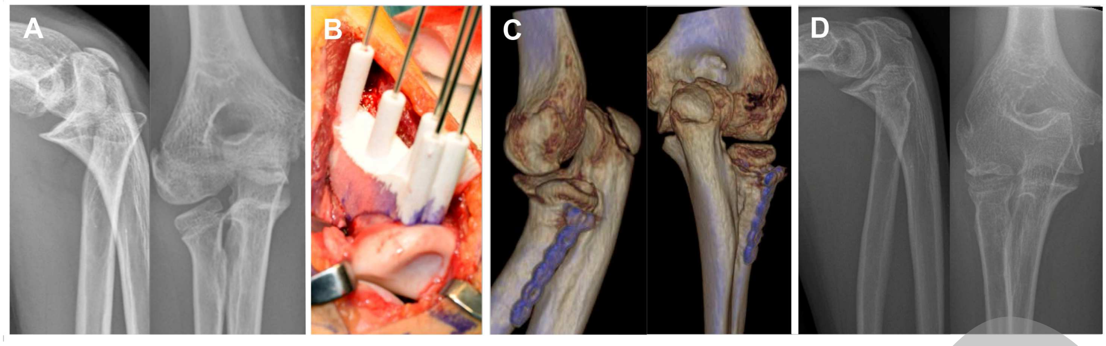
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